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Materials Requirements for Space Propulsion

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Introduction

There are already in the literature several excellent surveys in the same area as this paper [1,4,5,6]. In fact, there has been a recent symposium on the subject [11]. Nevertheless, a brief paper here may not be amiss since it is recognized that many of the attendees at this International Symposium may not have been exposed to the problems I will discuss. Therefore, before going into any detail on the materials problems I believe some explanation of the propulsion devices and their areas of application will also be appropriate [2,3,7]. (Since this is a high temperature technology symposium I will not mention low and room temperature problems, although there are many of these).

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Controlled space travel is largely a matter of imparting velocity changes, varying both in magnitude and direction, to the space vehicle. A spacecraft propulsion system is the device which will change the velocity of the spacecraft in either or both magnitude or direction. In order to change its velocity, the propulsion system must exert a force on the body. To exert a force artificially on a body in space, a mass must be accelerated from or energy must be discharged from the body, thus producing a reaction force on the body; or mass or energy must strike the body, adhering to or being reflected from it. The former method is used; the latter method is under analytical study with reference to the reflection of photons from the sun.

The factors of major importance in obtaining a given payload velocity change are the velocity with which the propellant is ejected from the vehicle by the propulsion system and the ratio of the weight of the vehicle plus propellant and payload to the final weight of the vehicle. (This ratio is frequently called mass ratio.) Another term which I might mention is specific impulse. The specific impulse is directly proportional to the exit velocity of the propellant. It is defined as the pounds of thrust (force) produced by the propulsion system for each pound of propellant discharged per second.

Space propulsion systems are, in general, referred to as rockets. They can be divided into thermal or electric rockets. The thermal rockets are either chemical or nuclear. In the chemical thermal rocket

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the combustion of fuel and oxidant forms a hot combustion gas (propellant) which is accelerated by expansion through the nozzle. In the nuclear thermal rocket the gaseous propellant is passed through a nuclear reactor and thereby heated. The hot propellant is expanded through the nozzle and so accelerated. The electric rocket depends upon an electrical power generating system for accelerating the propellant.

Liquid Propellant Chemical Rockets

The kinetic theory of gases is directly responsible for the need for high temperatures and associated high temperature materials problems in rockets. A propellant is heated in both the chemical and nuclear rocket. It is accelerated by expansion through the nozzle. Now, according to the kinetic theory of gases, the kinetic energy of a gas is dependent on the temperature or, in other words, temperature is a measure of kinetic energy. $\frac{1}{2}MV^2 = KT$, that is, the mean molecular velocity is proportional to absolute temperature. This relationship may be rewritten so that the mean molecular velocity is approximately proportional to the square root of the combustion temperature divided by the mass or mean molecular weight. Therefore, a high combustion temperature and a low mean molecular weight of combustion products are desired. Fig. 1 shows some liquid propellant combinations which are of current interest. The hydrogen-oxygen propellant combination is planned for the M-1 rocket engine, to be used in the Apollo Program, and for the J-2 engine which is being developed for the second stage of Saturn C-5. Note the combustion temperature of over 5500° F. What materials do we have to contain this temperature? Obviously, for any sustained duration of burning, none of our conventional metals or alloys will contain this temperature. Current practice is to assemble the rocket thrust chamber and expansion nozzle of tubing segments which regeneratively cool the rocket. These tubing segments are brazed together. One of the propellants goes through the tubing before injection into the combustion chamber. The chamber is therefore regeneratively cooled. A typical rocket chamber and nozzle are shown in Fig. 2. Rocket engine manufacturers have found themselves on the horns of a dilemma. Initially, commercially pure metals were used for tubing because of their high thermal conductivity. The high thermal conductivity is desirable for cooling the inner surface of the chamber. In time, with the use of higher combustion temperatures and pressures, it was found necessary to go to high temperature alloys. These, however, have much lower thermal conductivities. The wall thickness of the tubing has therefore been decreased to minimize the heat loss. Decreasing the wall thickness decreases the strength of the tubing of the structure. In addition, a mundane but real materials problem has been the joining of the tubing. Most high temperature brazes are very brittle. A rocket chamber is a dynamic structure. Conventional brazing alloys, as shown in Fig. 3, agressively attack the tubing material. The net result is that the designer does not know what the strength of the alloy is because a new alloy has been made. Careful selection of brazing alloys, with emphasis on tight fit, solves this problem.

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Solid Propellant Rockets

Although solid propellant rockets have been used for centuries, it is only within the last few years that they have been agressively promoted as boosters for space flight. They are now extensively used for missiles. A simplified sketch of a solid propellant rocket is shown in Fig. 4. The high temperature problem area is the nozzle, with particular reference to the throat. The casing for the solid propellant grain generally offers no insurmountable problem. Current solid propellant rockets are core burners; that is, they burn outwardly from a central hollow space which extends the length of the rocket. The propellant itself acts as thermal insulation, protecting the high strength casing from the combustion temperature and products during most of the burning. An additional layer of insulation between propellant and casing may provide further thermal insulation and differential thermal expansion adjustment.

Initially, rocket nozzles were fabricated from steel sheet. As the rockets increased in size and burning duration, it was found necessary to provide refractory abrasion and temperature resistant coatings. In time, in the throat area, even these were insufficient. Graphite was introduced as a nozzle insert and was very successful until the recent development of large solid propellant rockets. Many newer solid propellants of higher specific impulse have aluminum powder distributed through the grain to provide combustion stability. The aluminum oxidized. The abrasive aluminum oxide enlarged the nozzle throats, frequently unevenly, providing a poor basis of control.

The refractory metals have been investigated for application as nozzles or nozzle throat inserts. They have been moderately satisfactory. Unfortunately, these metals are refractory not only in temperature capability but in fabrication. They are particularly brittle in the cast, unworked condition, including welds. Nozzles fabricated of wrought refractory metals would frequently shatter, due to thermal shock, soon after propellant ignition. A. V. Levy has recently reported on a new solution to the nozzle problem [12]. Mr. Levy advocates the use of silver impregnated tungsten prepared by infiltration of liquid silver by capillary action into a porous isostatically pressed nozzle or shape of tungsten. The silver content is approximately 20% by volume and is connected by pores of an average size of four microns. Fig. 5 shows a photomicrograph of the silver-tungsten composite before firing. During firing the silver is melted out. This melting and vaporization provide heat absorption and cooling for the nozzle. In addition, this material has, at room and moderately elevated temperatures, almost as high a strength as forged tungsten. Also, it has greater ductility and a lower modulus. The ductility is higher, the thermal conductivity is higher, and the fracture strength is increased below the ductile-brittle transition temperature. Therefore it is less susceptible to thermal shock.

In this application the material performs in a much superior manner to forged tungsten or tungsten alloy. Yet, if one were to compare the two materials solely on the basis of tensile strength at high temperatures, one would choose the forged tungsten. However, analytical and experimental stress analysis of the nozzle during firing showed that the highest thermal stresses were obtained soon after ignition, when the refractory metal in the nozzle was below its transition temperature. This temperature region, below 800° F., is not one for which one would select tungsten or molybdenum. I am impressed by this material composite. I believe it is one of the few composites where the final properties have taken advantage of the desired properties of the components, rather than the properties not desired.

Nuclear Rockets

The next thermal rocket I wish to discuss is the nuclear rocket. I mentioned at the beginning of my talk that the specific impulse of a propellant was dependent upon the propellant having a low molecular weight and high temperature. Since we need no oxidant in a nuclear rocket, the heat being provided by the nuclear reactor, our molecular weight may be as low as 2, that of hydrogen. This is contrasted to 18, the molecular weight of water, the product of combustion of the hydrogen - oxygen motor. Temperatures here are dependent upon the reactor capability, and are not related to any combustion temperature. The nuclear rocket is under consideration for upper stages to provide space propulsion after launching by chemical rockets. Fig. 6 shows the payload capability of such a rocket as a function of propellant temperature. We see that increasing the gas temperature from 3000 to 5000° F. doubles the payload. Also, although it is not shown on this chart, other studies have indicated that the nuclear rocket must operate at temperatures over 3500° F. if it is to be competitive with the chemical rocket. This is due to the low bulk density of liquid hydrogen and to the high weight of the reactor. The reactor itself (Fig. 7) and the materials problems within the reactor and within the fuel elements pose severe problems. Considerable attention has been paid to graphite by the Los Alamos Scientific Laboratory [8]. A reactor, using graphite base elements, has been operated on the ground. Graphite has the advantage of excellent thermal shock resistance, high melting or vaporization point, and very easy fabrication. However, it reacts at high temperatures with hydrogen. Reference 9 indicates that studies are under way at the Argonne National Laboratory on tungsten matrix materials for fuel elements. Studies of compatibility of various materials with one another and with hydrogen at temperatures up to 5000° F. have been reported [13,14].

Requirements for fuel elements in the reactor may be summarized: The matrix and fissile material should not react with each other or with hydrogen. The elements should have adequate strength and resistance to repeated thermal shock and minimum fission damage. The materials selected should be capable of fabrication into required shapes. It is probable that material selection and combination will vary with reactor design which may, in turn, vary with mission requirement. There appears to be more potential and need for repeated re-start with the nuclear rocket compared with the chemical rocket.

Another difficult problem area for materials in the nuclear rocket is the nozzle. The nozzle may experience heat fluxes twice as great as those encountered to date in chemical rockets. Liquid hydrogen is available for regeneratively cooling the nozzle which may be fabricated, like chemical rocket nozzles, from nickel or nickel base alloys. Reference 10, an analytical study, concludes that nickel is only marginally suitable, if at all, for the regeneratively cooled throat of a nuclear rocket. Items 2 and 3 in Reference 10 indicate that the authors have diverted their attention to refractory metals which they are now studying for rocket nozzle application. They would use these materials in sheet structures without regenerative cooling, depending upon high temperature operation and cooling by radiation. Another possibility is to fabricate the nozzle from tungsten but back it with a supporting structure, perhaps of graphite.

I feel that one type of material which has been neglected for such applications is the dispersion hardened alloy. Fig. 8 shows schematically the thermal conductivity of dispersed phase hardened materials in comparison with those of the more common solid solution strengthened alloys. I am not referring here to dispersion hardened materials of the precipitation hardening type, but to a material which has no solute in the matrix. When I have this I have almost no effect upon thermal conductivity. These materials, therefore, look very promising both from the viewpoint of maintenance of strength and thermal conductivity at high temperature. Recent commercial development of a new nickel base alloy, hardened by thoria, has utilized the very sensible approach of reducing the amount of dispersant to that barely necessary for hardening, thereby retaining a large proportion of the basic ductility of the matrix [15]. Such materials have sufficient capability for forming tubing, etc., so that they may find themselves being used for such applications. The 2% thoria hardener does not prevent brazing.

Another approach frequently suggested is the use of refractory metal, such as tantalum and niobium tubing, in the same manner that nickel-base and high temperature alloy tubing have been used for chemical rockets. Since the propellant we are considering is hydrogen in a temperature range from -420° F. to several thousand degrees F. and, considering also, that one of the methods of making tantalum is to expose it to hydrogen to form tantalum hydride powder, I cannot help but feel that some of the advocates of refractory metals in such applications have not given the environment sufficiently careful consideration. Formation of refractory metal hydride or powder would be rather disconcerting in a rocket.

Electric Rockets

This class of rockets differs markedly from the thermal rockets I have described. The primary difference is the use of a propellant which can be readily ionized and accelerated electrically to very high velocities. The molecular weight of the propellant is a minor consideration (except for an electrothermal rocket, a limited concept employing electric power to heat the propellant). The equations are similar to those for chemical propulsion:

$$V = k\sqrt{\frac{QE}{m}}$$

where

V = molecular velocity
Q = voltage imposed on particles or molecules
E = electrical charge imposed on particles or molecules
m = molecular (particle) weight.

Since the voltage limitation is very high, the low molecular weight of the propellant is less significant, and much higher specific impulses appear possible than with thermal rockets.

Cesium is most frequently mentioned as a propellant. The ionization potential for cesium is below that of the work function of tungsten and some other refractory metals; therefore, cesium may readily be ionized on a tungsten electrode. The positively charged cesium ion leaves the electrode surface and is rapidly accelerated by the electric field downstream. Cesium also has a low melting point, low heats of vaporization and fusion, and a low specific heat. There is a need for a porous material of very fine pore size for the electrodes. Pore sizes and distribution of one micron diameter have been suggested. This close spacing is believed necessary to provide a high percentage of ionized cesium passing through the porous electrodes. High efficiency is also encouraged by the use of high electrode temperatures (2000° F. and over). The maintenance of these temperatures and of pore sizes, with neither choking nor enlargement, for hundreds and thousands of hours will undoubtedly be a problem.

Other problems include the development of ceramic electrical insulator and insulator to metal seals, which must be resistant to and stable in the presence of very high vacuums and/or alkali metal vapors, and the development of sputter resistant films.

Although the electrode creates a very specific problem, it has not received very much attention because of the greater profusion of materials problems in another area, namely, the generation of the electric power needed for the electric rockets. Since Professor Nottingham is discussing direct heat energy conversion, I will say a few words on the materials problems anticipated in nuclear turbo-electric systems. Fig. 9 shows a conceptual view of an electric space vehicle. Notice the very large radiator area. This presents a beautiful target for meteorites in space. Unfortunately, we can neither duplicate velocities within the laboratory that we anticipate in space nor can we accurately predict the concentration of meteorites in space. However, we have been able to measure the effects of some variation in velocity and projectile material in the laboratory. Fig. 10 certainly indicates that high velocities have rather drastic effects. Further studies have indicated that protective covers or bumpers may be beneficial. Since the only way of losing or rejecting heat from our system is by direct radiation, the addition of a protective cover will tend to decrease efficiency. The materials which appear desirable for impact resistance are also those which are difficult to fabricate, assemble, and apply as bumpers [4].

Turning next to the turbine-boiler-condenser area of the nuclear turbo-electric system (Fig. 11) cycle analyses have indicated that it is necessary to obtain a system specific weight of 50 pounds per kilowatt, or below. This therefore will require a radiator temperature of 1500° F. or thereabouts. This, of course, imposes still higher temperature requirements upon the remainder of the system. (So far as total power is concerned, one example will suffice: one megawatt to televise a picture from Mars to Earth.)

Fig. 12 indicates the temperature and pressure region of concern to us and explains our interest in alkali metals. There are many problems which must be considered here. One is mass transfer which is the solution of a container material or component of a container material at a hot temperature and redeposition as a plugging powder at a cooler temperature and location. General compatibility or solubility is another problem. It has been known for years that retention of an oxide or impurity layer on a surface contributes to lubrication. Since the alkali metals are excellent solvents for oxides, it is apparent that they will also hinder effective boundary lubrication. In addition, since these systems are supposed to operate in space for a year or more unattended, we must consider the possibility or liklihood of selective vaporization of the alloy elements of the container materials. For quite some time now, there has been strong emphasis on the fact that our needed properties for missiles and space use are properties which we need for only short duration. In considering space power systems we are returning to long periods of time -- of a year or more.

The niobium 1% zirconium alloy generally favorably considered for containment of alkali metals appears to have only marginal strength for some turbo-electric applications. Higher strength alloys pose the problem I have recently mentioned of selective vaporization. Poor weldability, selective solubility, and mass transfer are other possibilities.

Another problem is ground simulation for check-out of these systems. We know that the environment affects the properties of many materials. If we have traces of oxygen in our ground system, these can be absorbed very readily by the refractory metals of which it is made. The oxygen may penetrate and diffuse through the refractory metal, be dissolved in the alkali metal, the alkali metal oxide may re-deposit elsewhere in the system, giving misleading information or plugging. In addition, it has been found that alkali metals containing higher percentages of oxygen are much more agressive in their attack on container materials. All these effects are under vigorous attack and study in various laboratories, and it may be hoped that solutions will soon be found.

In conclusion, I would like you to consider one aspect of materials which I have not discussed, namely, reliability. Repair in space may have its theoretical advantages but spare parts are not readily available.

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List of Figures